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Estimating Plume Dispersion
A Comparison of Several Sigma Schemes

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Centerline values of surface concentration are estimated using the Gaussian plume model and compared with the concentration values determined during five field experiments. Comparison of the concentration estimates with the measurements suggests that Draxler's scheme results in the smallest mean fractional error in the concentration estimates and the smallest variance of the fractional errors. Two alternative characterization of the dispersion, formed by altering Draxler's scheme to be independent of release height, are shown to perform almost as well as Draxler's scheme.

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Estimating Plume Dispersion—A Comparison of Several Sigma Schemes

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ABSTRACT

The lateral and vertical Gaussian plume dispersion parameters are estimated and compared with field tracer data collected at 11 sites. The dispersion parameter schemes used in this analysis include Cramer's scheme, suggested for tall stack dispersion estimates, Draxler's scheme, suggested for elevated and surface releases, Pasquill's scheme, suggested for interim use in dispersion estimates, and the Pasquill–Gifford scheme using Turner's technique for assigning stability categories. The schemes suggested by Cramer, Draxler and Pasquill estimate the dispersion parameters using onsite measurements of the vertical and lateral wind-velocity variances at the effective release height. The performances of these schemes in estimating the dispersion parameters are compared with that of the Pasquill–Gifford scheme, using the Prairie Grass and Karlsruhe data. For these two experiments, the estimates of the dispersion parameters using Draxler's scheme correlate better with the measurements than did estimates using the Pasquill–Gifford scheme. Comparison of the dispersion parameter estimates with the measurements suggests that Draxler's scheme for characterizing the dispersion results in the smallest mean fractional error in the estimated dispersion parameters and the smallest variance of the fractional errors.

Centerline values of surface concentration are estimated using the Gaussian plume model and compared with the concentration values determined during five field experiments—three for near-surface releases and two for elevated releases. Comparison of the concentration estimates with the measurements from the five field experiments suggests that Draxler's scheme for characterizing the dispersion results in the smallest mean fractional error in the concentration estimates and the smallest variance of the fractional errors. Two alternative characterizations of the dispersion, formed by altering Draxler's scheme to be independent of release height, are shown to perform almost as well as Draxler's scheme.

1. Introduction

Participants of the American Meteorological Society workshop on stability classification schemes and sigma curves (Hanna *et al.*, 1977) recommended refinement of methods for estimating the vertical and lateral dispersion parameters used in Gaussian plume models, especially for elevated releases. Routine analyses of Gaussian plume dispersion typically employ the Pasquill–Gifford curves (Turner, 1970). But, the σ_z (standard deviation of the vertical concentration distribution) curves of that scheme were based on near-ground level releases over flat terrain (Pasquill, 1976). The site roughness length was approximately 3 cm for the short-range (0.1 to 1 km) studies of dispersion. The data employed for extrapolation of the short-range dispersion results to distances of 10–100 km had mixed roughness of approximately 30 cm. As discussed by Hanna *et al.* (1977), the Pasquill–Gifford curves are extrapolated to releases at heights and distances far beyond the supporting measurements. To promote better practices, the workshop participants reviewed the bases and limitations of several of the more popular dispersion parameter estimation schemes. Hanna *et al.* (1977) suggested that the standard deviation of the crosswind concentration distribution, σ_y, might be viewed as

$$\sigma_y = \sigma_v T f_y, \tag{1}$$

where σ_v is the standard deviation of the horizontal crosswind component of the wind, T is the downstream travel time of the pollutant, and f_y is a nondimensional function of travel time. For an elevated source, when σ_z is less than source height, it was viewed as

$$\sigma_z = \sigma_w T f_z, \tag{2}$$

where σ_w is the standard deviation of the vertical component of the wind, and f_z is a nondimensional function, primarily a function of travel time. The small-angle approximations $\sigma_v T = \sigma_a X$ and $\sigma_w T = \sigma_e X$, where σ_a is the standard deviation of the horizontal wind angle and σ_e is the standard deviation of the vertical wind angle, allow restatement of (1) and (2) in the various forms mentioned in the Hanna *et al.* workshop summary. Draxler's (1976) and Pasquill's (1976) characterizations of f_y were mentioned as examples of currently available estimates of f_y. Drax-

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ler's (1976) estimates of f_z were mentioned, but it was suggested that the scatter in the data precluded recommending a detailed form for f_z.

Previous work on estimating plume dispersion (Irwin, 1979) was reviewed by a peer panel (Randerson, 1979). This review and others stressed the usefulness of examining errors one might encounter in using a particular characterization of dispersion as compared to using other available systems. The present discussion focuses on the simpler characterizations of f_y and f_z. Although these characterizations do not allow for direct parameterization of the dispersion using surface-layer or mixed-layer scaling, they do offer promise for use in routine investigations, since they require the least sophisticated input data for schemes of this kind. The present discussion has a twofold purpose: 1) To summarize the performance of simple characterizations of f_y and f_z over a variety of conditions and to present comparisons with the routinely used Pasquill–Gifford scheme. 2) To improve the "routine" tools, evidence is presented to show that the performance of the Pasquill–Gifford scheme can be matched and often surpassed by the techniques of Cramer (1976), Draxler (1976), and Pasquill (1976). These new techniques are robust and are not inclined to erratic behavior over a variety of dispersion conditions.

2. Analysis of experimental data

Tables 1 and 2 summarize the field data used in this analysis. Included in the tables are the sources of the data and a summary of meteorological and dispersion data available. The data include those used by Draxler (1976) in his initial investigations of the forms of f_y and f_z, to which have been added the data from Round Hill (Cramer *et al.*, 1958), Mountain Iron (Hinds and Nickola, 1967; Hinds, 1968), Hanford-67 (Nickola, 1977), and Karlsruhe (Thomas *et al.*, 1976; Thomas and Nester, 1976).

TABLE 1. Summary of dispersion experiments having near-surface release heights.

Site	Release Height (m)	Receptor Height (m)	Meteorological Data	Dispersion Data, Tracer
Round Hill I (Cramer, Record and Vaughan, 1958)	0.3	2.0	U, σ_a, σ_θ at 2 m ΔT (12 - 1.5 m)	Concentrations along arcs (50, 100, 200 m), 10 min releases, SO_2 gas.
Round Hill II (Cramer, Record and Vaughan, 1958)	0.5	1.5	U, σ_a at 2 m ΔT (12 - 1.5 m)	Concentrations along arcs (50, 100, 200 m), 10 min releases, SO_2 gas.
Prairie Grass (Barad, 1958) (Haugen, 1959)	0.46	1.5	U, σ_a, σ_θ at 2 m ΔT (16 - 2 m)	Concentrations along arcs (50, 100, 200, 400, 800 m), 10 min releases, SO_2 gas.
N.R.T.S. A&B (Islitzer and Dumbauld, 1963)	~1.0	~1.0	U, σ_a, σ_θ at 4 m ΔT (16 - 4 m) ΔT (8 - 1 m)	σ_y and Xmax (100, 200, 400, 800, 1600, 3200 m), 60 min releases, uranine dye.
Green Glow (Fuquay, Simpson, and Hinds, 1964)	2.5	1.5	U, σ_a at 2.1 m Ri (15.2 - 2.1 m)	σ_y (200, 800, 1600, 3200, 12800, 25600 m), 30 min releases, zinc sulfide.
Hanford-30 (Fuquay, Simpson, and Hinds, 1964)	2.5	1.5	U, σ_a at 2.1 m Ri (15.2 - 2.1 m)	σ_y (200, 800, 1600, 3200, 12800 m), 60 min releases, zinc sulfide.
Ocean Breeze (Haugen and Fuquay, 1963)	2 to 3	1.5	U, σ_a at 3.7 m ΔT (16.5 - 1.8 m)	σ_y (1200, 2400, 4800 m) 30 min releases, zinc sulfide.
Dry Gulch (Haugen and Fuquay, 1963)	2 to 3	1.5	U, σ_a at 3.7 m ΔT (16.5 - 1.8 m)	σ_y (853, 1500, 2301, 4715, 5665 m), 30 min releases, zinc sulfide.
Mountain Iron (Hinds and Nickola 1967); (Hinds, 1968)	~2.0	1.5	U, σ_a at 3.66 m ΔT (18 - 1.8 m) ΔT (91.4 - 1.8 m)	σ_y (variable, from 260 m to 11400 m) Several 5 min releases, mostly 30 min releases, zinc sulfide.
Hanford-67 (Nickola, 1977)	2.0	1.5	U at 2 m σ_a at 1.5 m ΔT (15.2 - 0.9 m)	σ_y (200, 400, 800, 1200, 1600, 3200, 5000, 7000, 12800 m), 10 to 30 min releases, zinc sulfide, fluoresein (uranine), rhodamine B, krypton-85.

TABLE 2. Summary of dispersion experiments having elevated release heights.

Site	Release Height (m)	Receptor Height (m)	Meteorological Data	Dispersion Data, Tracer
Suffield (Walker, 1965)	7.42 and 15	Surface	U, σ_a, σ_e at 8 m and 16 m ΔT (4 - 0.5 m)	σ_y (27.4 to 1097.3 m) 30 to 60 min releases, glass spheres
NRTS (Islitzer, 1961) (Bowne, 1960)	46	1	U, σ_a, σ_e at 43 m ΔT (43 - 3 m)	Sutton (n, C_y, C_z) (150 to 3400 m), 30 min releases, uranine dye
Hanford-67 (Nickola, 1977)	26 and 56	1.5	U, σ_a at 26 and 56 m ΔT (15.2 - 0.9 m)	σ_y (200 to 4000 m), 10 to 30 min releases, zinc sulfide, fluoresein (uranine), rhodamine B, krypton-85
Ågesta (Högström, 1964),	50	Smoke puff photography	σ_e estimates at 50 m Diffusion time Stability parameter	σ_z (100 to 1500 m) σ_z (20 to 400 s) (Sampling time about 60 min)
Hanford (Elderkin et al., 1963) and (Hilst and Simpson, 1958)	56	1.5 for σ_y Vertical array about release height for σ_z	U, σ_a at 61 m Ri (76 - 15 m) for σ_y ΔT (91 - 30 m) for σ_z	σ_y (100 to 1600 m) σ_z (152 to 1524 m) 15 to 60 min releases, fluorescent dye
Karlsruhe (Thomas et al., 1976) (Thomas and Nester, 1976)	100	Surface	U, σ_a, σ_e at 100 m ΔT (100 - 30 m)	σ_y and σ_z (variable 100 to 3900 m), 20 to 60 min releases, tritiated water vapor, halogenated hydrocarbons
Porton (Hay and Pasquill, 1957)	140 to 255	Vertical array about release height	U, σ_e at release height ΔT (7 - 1.2 m)	σ_z (variable 100 m to 500 m), 30 min releases, lycopodium spores

The σ_a, σ_e, and U values were either computed or were available from the study reports. It was assumed that bias because of instrumentation performance or data processing procedures would affect the performance of the estimation schemes equally and therefore would not interfere with a valid comparison of the schemes. We found it sufficient to characterize stability as stable or unstable from the near-surface data for temperature difference ΔT, Richardson number Ri, or a stability parameter.

Measurements of the wind speed at or near the release height were provided for all sites except Ågesta. Each characterization of σ_z given by Högström (1964) represents the synthesis of several trials. A mean wind speed to associate with each σ_z characterization was derived using the σ_z results listed in terms of downwind distance (Table 3 of Högström) and using the results given for σ_z as a function of travel time (Fig. 17 of Högström). The mean wind speed was derived by selecting cases when $\sigma_z(T) = \sigma_z(X)$ and solving for U as X/T.

At two sites, Prairie Grass and Karlsruhe, sufficient data were provided to compute both σ_y and σ_z either through the use of onsite σ_e and σ_a data or through the use of the Pasquill–Gifford scheme as discussed by Turner (1970). The Karlsruhe data listed Pasquill stability categories that were estimated using Turner's (1964) characterization of Pasquill's stability criteria. Pasquill stability categories were computed for the Prairie Grass data using Turner's (1964) characterization and the cloud height and cloud amount data presented in the Prairie Grass data summaries.

a. Treatment of dispersion data

All data were converted to the same format. The values of σ_y were either available from the published data or could be derived from the lateral concentration profiles of dosage along sampling arcs (as in the cases of Round Hill and Prairie Grass).

The vertical dispersion parameters were computed for Round Hill, Prairie Grass, and NRTS A&B by assuming conservation of the tracer with a binormal distribution. For a point source, the centerline concentration χ_0 can be estimated as:

$$\chi_0 = Q/(2\pi\sigma_y\sigma_z U)[\exp-(1/2)(z - H/\sigma_z)^2 + \exp-(1/2)(z + H/\sigma_z)^2], \quad (3)$$

where Q is the emission rate, z the receptor height, H the release height, and U the mean wind speed. Eq. (3) can be solved for σ_z given χ_0, H and z using iterative techniques. For near-surface releases in which both H and z are nearly zero, Eq. (3) can be simplified and σ_z can be estimated as

$$\sigma_z = Q/(\pi\sigma_y\chi_0 U). \quad (4)$$

Draxler (1976) employed Eq. (4) to compute σ_z but explained that (4) is valid when there is no significant loss of material during transport. Over the first 100 m of travel, this assumption appears reasonable for Prairie Grass (Barad and Haugen, 1959). However, for the greater distances at NRTS, Islitzer and Dumbauld (1963) found from 10 to 54% depletion (about 26% at 200 m and about 34% at 400 m). For these cases, ratios of observed to computed σ_z, assuming no loss of material during transport, varied from 0.4 to 4.7, with most computed values within a factor of 2 of the observed values. Moreover, Simpson (1961) analyzed several dispersion trials conducted during the Hanford field tests. His results suggest that computing σ_z by assuming no loss of material during transport, when, in fact, tracer is depleted through removal processes, can lead to overestimates of σ_z by a factor of 1.78 at 200 m, 4.7 at 800 m, and 13.4 at 3200 m.

Because measured σ_z values for the near-surface releases were few, the compromise was made to use σ_z values computed assuming no material loss during transport. Mass balance analyses at the 100-m downwind arc (Barad and Haugen, 1959) suggest that material losses generally are less than 10 to 16%, for the near-surface SO_2 releases conducted during the Prairie Grass field tests. We assume material losses for the near-surface releases of SO_2 at Round Hill would be similar to that experienced during the Prairie Grass tests. It is expected that SO_2 would be less susceptible to surface depletion than uranine dye. We conclude that the σ_z values associated with the SO_2 releases at Round Hill and Prairie Grass are within ±25 to 50% of the true values. The σ_z values for the NRTS near-surface releases are considered more suspect. Errors in the σ_z values associated with these releases may be as large as a factor of two for downwind transport less than 800 m, and even larger errors may occur for transport beyond 800 m.

The σ_z values for the elevated releases were available from information published. The NRTS data, expressed in terms of Sutton's coefficients, n, C_z, C_y, were converted to σ_z values (Table 6-1 of Turner, 1970). Graphic plots of the maximum concentration at each downwind arc were used to define the peak surface concentration χ_p and the distance to the peak concentration d. The coefficients were then computed in terms of χ_p and d, assuming bivariate Gaussian-plume dispersion (Bowne, 1960). The Ågesta σ_z values (Högström, 1964) were derived from photographs of smoke puffs, viewed from the vantage of the release point, taken as the puffs advected downstream. Högström analyzed the photographs for the variation in the transport of the puff centers and for the overall growth of the puffs during transport. He computed the vertical and lateral dispersion parameters and then averaged parameters of trials with similar stability. The Hanford σ_z values (Hilst and Simpson, 1958) were derived using a sampling procedure similar to that used by Hay and Pasquill (1957) at Porton. In both cases, cylindrical impaction samplers were attached to the tethering cable of a small captive balloon, and the sampler array was approximately centered at the release height. At Karlsruhe (Thomas *et al.*, 1976; Thomas and Nester, 1976) the σ_z values were computed using the individual measurements of the concentration observed on the array of surface samplers. For the cases used in this analysis, there were five samplers located on each of the five arcs. A least-squares best fit to the 25 surface concentrations by a bivariate Gaussian-plume model was used to estimate values for the lateral and vertical dispersion for each trial. The Karlsruhe tracer data suggest that the absolute percentage errors in the σ_z values range from 3 to 114% with a median value of 16%, and the absolute percentage errors in the σ_y values range from 10 to 154% with a median value of 32%. The greater uncertainty in the σ_y values in comparison to the σ_z values likely relates to the availability of only five values for ground-level concentration along each downwind arc.

b. Comparison of dispersion parameter estimates

Table 3 summarizes the equations suggested by Draxler (1976), Pasquill (1976) and Cramer (1976) for characterizing f_y and f_z. The vertical and lateral dispersion parameters were estimated using (1) and (2) for each downwind arc using the models listed in Table 3. For these estimates, the vertical and lateral velocity variances at release height were used. Statistics comparing the estimated dispersion parameters with the measured values were initially computed for each possible combination of release height (elevated and near-surface) and stability stratification (stable and unstable). One of the more useful statistics for characterizing the errors was found to be the fractional error

$$e = 2(P - O)/(P + O), \tag{5}$$

where P is the model estimate and O is the measured value. The fractional error is logarithmically unbiased, having the same numerical value, although different signs, for either an overestimate of n times the measured value or an underestimate of $1/n$ times the measured value. The distributions of the fractional errors were found to be more nearly normal than the distributions of the residuals or the distributions of the ratios formed by dividing the model estimate by the measured value. The distributions of the residuals and the ratios were found to be highly skewed, being neither normally nor lognormally distributed. Scatter plots of estimates versus measurements, plots of the cumulative frequency distributions of the residuals, and the ratios were constructed in the course of this research. To convey in a quan-

TABLE 3. Summary of equations used for the functions f_y and f_z to characterize the growth of lateral and vertical dispersion as a function of travel time T (s), or of downwind distance X (m). Model 1 is Draxler's (1976) and provides for variation of the functions with release height and stability. Model 2 is Cramer's (1976), where no buoyancy-induced dispersion is assumed. Model 5 is Pasquill's (1976).

	Lateral dispersion		Vertical dispersion	
Model 1	Elevated releases	$1/f_y = 1 + 0.9(T/1000)^{0.5}$	Elevated releases	
			unstable	$1/f_z = 1 + 0.9(T/500)^{0.5}$
			stable	$1/f_z = 1 + 0.945(T/100)^{0.806}$
	Surface releases		Surface releases	
	unstable	$1/f_y = 1 + 0.9(T/300)^{0.5}$	unstable	$f_z = (0.3/0.16)(T/100-0.4)^2 + 0.7$
	stable	$1/f_y = \begin{cases} 1 + 0.9(T/300)^{0.5} & T<550 \\ 1 + 28/(T)^{0.5} & T>550 \end{cases}$	stable	$1/f_z = 1 + 0.9(T/50)^{0.5}$
Model 2		$f_y = (50/X)[(X-5)/45]^{0.5}$		$f_z = 1$
Model 3		$1/f_y = 1 + 0.9(T/1000)^{0.5}$	unstable	$f_z = 1$
			stable	$1/f_z = 1 + 0.9(T/50)^{0.5}$
Model 4		$1/f_y = 1 + 0.9(T/1000)^{0.5}$	unstable	$1/f_z = 1 + 0.9(T/500)^{0.5}$
			stable	$1/f_z = 1 + 0.9(T/50)^{0.5}$
Model 5		$1/f_y = \begin{cases} 1 + (X/2500)^{0.5} & X<10{,}000 \\ 3\ (X/10{,}000)^{0.5} & X>10{,}000 \end{cases}$		Pasquill-Gifford dispersion scheme

titative sense the subjective impressions of model bias and precision of model estimates gained from these plots, the illustrations of mean fractional error similar to those employed by Gryning and Lyck (1980) were chosen. The mean fractional error is a measure of average bias, and the standard deviation of the fractional errors is a measure of the scatter or precision of the estimates.

The dispersion results from the field tests were reviewed for consistency to determine if the variation of release times and terrain types between experiments might affect the comparison results. The release times for the tests range from 5 to 75 min. Most releases were for 20 min or longer, except for several of the Mountain Iron field tests and for the 10-minute releases conducted at Round Hill and Prairie Grass. Of the 113 Mountain Iron tests, 58 had complete meteorological data available at the release point. Of the 58 tests, seven were for 5-min releases and 12 were for 15-min releases. Hinds and Nickola (1967) treated the 15- and 30-min results as a homogeneous group in their analyses, because they saw no discernible differences in these data. They reported that the decrease in the measurements of exposure with distance was more rapid for the 5-min releases in comparison to the other data. This was attributed to the increased significance of longitudinal dispersion for the puff-like 5-min releases. Inspection of the variation of the σ_y values with distance revealed no discernible differences between the 5-min releases in comparison to the 15- and 30-min releases. For short travel distances, 10- and 30-min σ_y values are nearly the same; hence, the σ_y values for Round Hill and Prairie Grass were grouped with the data from the other experiments. The Round Hill and Prairie Grass σ_z values were grouped with the data from the other experiments which generally had release times of 30-min or greater (Pasquill, 1976). Regarding terrain effects on dispersion results, Hinds and Nickola (1967) concluded from their analysis of the Dry Gulch, Prairie Grass, Green Glow, and Mountain Iron data that the influence of local climate and terrain on dispersion is increased during stable atmospheric conditions and decreased during unstable conditions; that is, the atmospheric mixing is sufficient during moderately unstable atmospheric conditions to outweigh local terrain effects. Of the 58 Mountain Iron field tests included in our analysis, only seven were conducted during stable stratification. The variation of σ_y with distance for these seven tests was similar to the variation of σ_y seen for the tests conducted during unstable stratification. The field tests used in the vertical dispersion parameter comparisons were conducted in flat to gently rolling terrain. It was concluded that the dispersion results used in the following comparison analyses can be treated as a homogeneous group typical of dispersion over flat to gently rolling terrain.

The results for seven downwind distance ranges were used to assess the variation in the comparison results as a function of distance downwind. Table 4 gives, for the lateral dispersion parameter comparisons, the distance ranges used in these analyses and the number of cases in each range as a function of

TABLE 4. For the lateral dispersion parameter comparisons, the number of cases within each distance range as a function of release height and of stratification for the full data set.

Release Height	Stratification	Downwind Distance (km)							
		.03 to .06	.06 to .15	.15 to .55	.55 to 1.75	1.75 to 5.40	5.40 to 17.0	17.0 to 30	Total
Elevated	Stable	11	25	52	111	70	23		292
	Unstable	8	37	96	107	33	2		283
Near-Surface	Stable	53	61	147	190	115	46	11	623
	Unstable	44	58	120	270	244	92		828

release height and of stratification. The distance dependence of the comparison results for the lateral dispersion parameter estimates is illustrated in Fig. 1. Because the number of cases available for analysis at each distance varies, it is important to assess the results given in Fig. 1 with reference to Table 4.

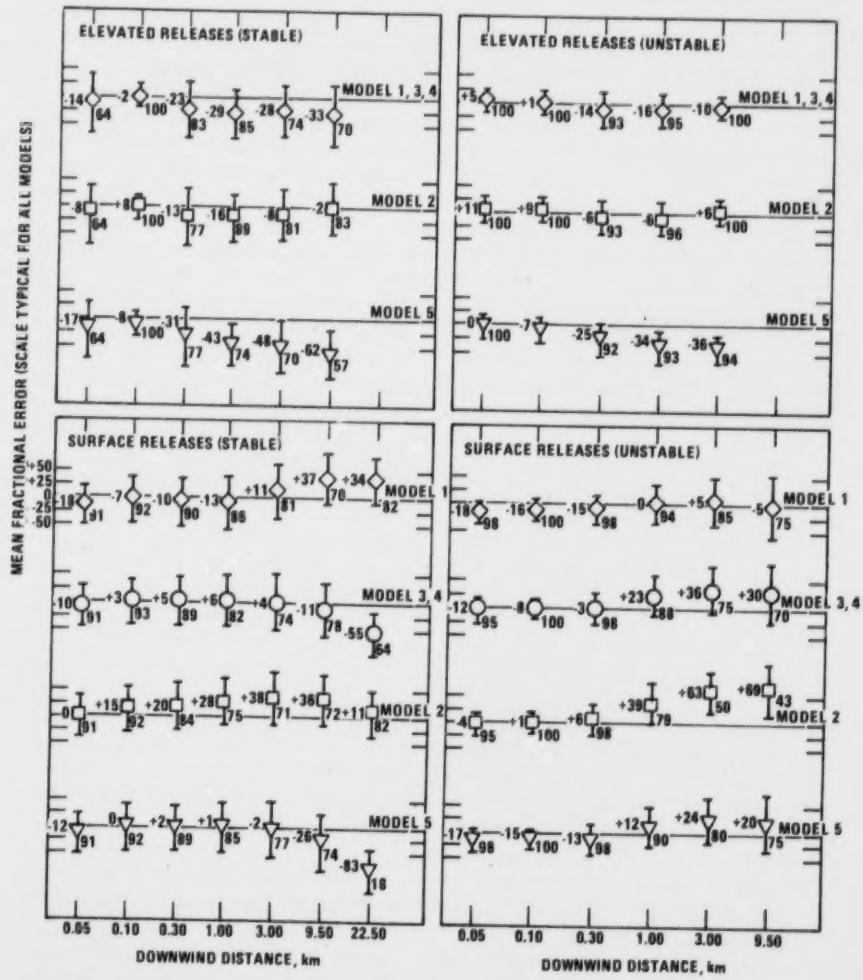

FIG. 1. Comparison of the measured lateral dispersion parameters with those estimated using the five dispersion parameter characterizations listed in Table 3, for the full data set. The number to the lower-right of each symbol is the percent of the estimated values within a factor of 2 of the measured values. The bars depict the mean fractional error plus or minus one standard deviation. The mean fractional error (percent) is given to the left of each symbol.

Models 1, 3 and 4 use the same characterization for estimating the lateral dispersion parameter for the elevated releases. The results depicted for the elevated releases (Fig. 1, top) suggest that overall, Model 2 (Cramer, 1976) had the least bias and that overall, Model 5 (Pasquill, 1976) had the largest bias for the elevated releases. For the near-surface releases (Fig. 1, bottom), Model 5 had the smaller bias and had more cases within a factor of two in comparison to Model 2. There was a trend for Models 3, 4 and 5 to underestimate the lateral dispersion parameters at the farthest downwind distances during stable stratification.

The 11 cases in the downwind distance range from 17 to 30 km are from the Green Glow field experiment (Fuquay *et al.*, 1964). The wind speeds were steady during these trials. The reported σ_a values for the Green Glow and Hanford-30 experiments would likely be larger if an averaging time shorter than 20 s had been used in the σ_a computations. However, there are other possible explanations for the underestimates of the σ_y values in addition to the averaging time associated with the σ_a values. For instance, comparison of the low-level horizontal wind directions at the beginning and end of the 30-min emission periods revealed changes in wind direction of 10° or more in six of the 11 cases. The dispersion estimation schemes assume steady-state meteorological conditions during transport downwind. It is therefore possible that variation in the transport direction during the releases may have resulted in unexpectedly large values of horizontal dispersion. Also, at larger transport distances, it is possible that significant contributions to the lateral dispersion may occur because of variation of the horizontal wind direction with height. The differences between the 2-m- and 30-m-level wind directions, observed on the meteorological tower near the release point, were generally between 7 and 10° for these 11 trials. Pasquill (1976) suggested that variation in horizontal wind direction with height should be considered for dispersion estimates at distances beyond 20 km. For the 11 cases from the Green Glow experiment, Pasquill's (1976) scheme for estimating the additional lateral dispersion resulting from wind direction shear in the vertical eliminates the bias to underestimate σ_y. The change in the characterization of the lateral dispersion parameter for travel times beyond 550 s by Model 1 (Draxler, 1976) for near-surface releases is made to compensate for the additional lateral dispersion due to horizontal wind direction shear in the vertical. It may prove difficult to acquire the data necessary to assess the additional lateral dispersion due to this effect. Hence, for routine analyses, the pragmatic solution may be the use of modeling methods as proposed by Cramer (1976), where the lateral dispersion is nearly linearly proportional to downwind distance.

Fig. 2 depicts the distance dependence of the comparison results for the vertical dispersion parameter estimates. Table 5 gives, for the vertical dispersion parameter comparisons, the number of cases in each distance range as a function of release height and stratification. No results are depicted in Fig. 2 for Model 5 because, for the vertical dispersion parameter, Model 5 employs the Pasquill–Gifford scheme, which is discussed later. Comparison of Figs. 1 and 2 suggests that the standard deviations of the fractional errors and the mean fractional errors were larger for the vertical dispersion parameter comparisons than were typical for the lateral dispersion parameter comparisons. This suggests that the estimates of the lateral dispersion parameter were more reliable than the estimates of the vertical dispersion parameter. The distances downwind having data for comparisons were more limited for the vertical than for the lateral dispersion parameter comparisons.

Of the four models compared in Fig. 2, Model 1 (Draxler, 1976) had the smallest bias. A limitation was seen in the use of Model 1 for the near-surface releases during unstable stratification. Draxler derived his characterization of the vertical dispersion for near-surface releases during unstable stratification from a regression analysis applied to the Prairie Grass data. The trend in the results for Model 1 clearly reflects the second-order polynomial fit. Beyond 800 m, the results for Model 1 reveal a strong tendency to increasingly overestimate the vertical dispersion parameter as downwind distance increases. The farthest downwind arc at Prairie Grass was 800 m. Models 3 and 4 are alternative characterizations of the dispersion parameters that eliminate the release-height dependence incorporated in Draxler's scheme; these models formed using parts of Draxler's and Cramer's schemes, performed as well as Draxler's model. The strong tendency for Model 2 (Cramer, 1976) to overestimate the vertical dispersion parameter during stable stratification may result from ignoring the depth of the nocturnal mixed surface layer in characterizing the vertical dispersion parameter. Limiting of the vertical dispersion during stable stratification is a provision of Cramer's model. However, sufficient data, such as detailed profiles of the variance of the vertical velocity fluctuations, were not available for the depth of the nocturnal mixed surface layer to be specified confidently.

Tables A and B in the Appendix present some of the statistics computed for the comparisons on the full data set. These statistics confirmed the trends seen in Figs. 1 and 2. The correlations between model estimates versus measured values were lower for the elevated releases, especially for the vertical dispersion parameter comparisons. The correlations were stronger for lateral dispersion parameter comparisons than for the vertical dispersion parameter comparisons. The statistical results support the conclusions that there is greater uncertainty associated with the ver-

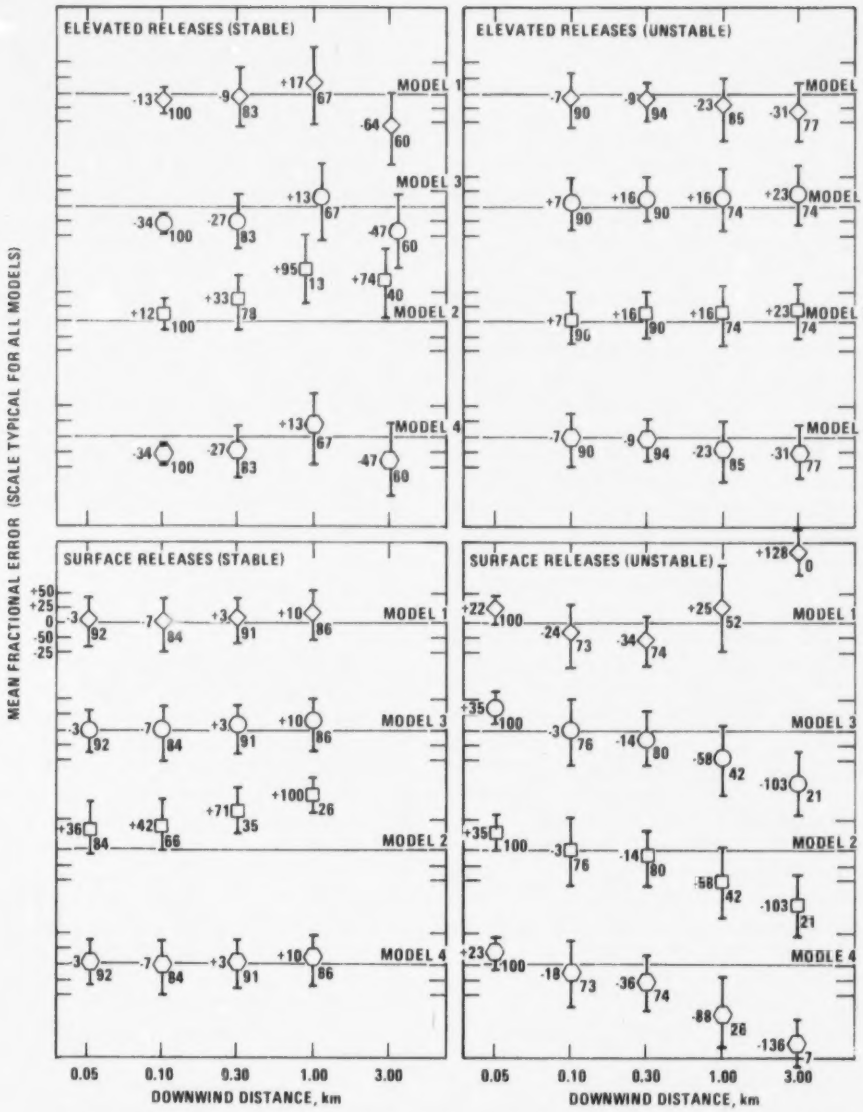

FIG. 2. Comparison of the measured vertical dispersion parameters with those estimated using the first four dispersion parameter characterizations listed in Table 3, for the full data set. Otherwise as in Fig. 1.

tical dispersion parameter estimates in comparison with the lateral dispersion parameter estimates, and that there is greater uncertainty associated with the estimates for the elevated releases than for the surface releases.

Extrapolation of the results illustrated in Figs. 1 and 2 to greater downwind distances cannot be accomplished without uncertainty. At downwind distances greater than 15–20 km, the contribution to the lateral dispersion due to horizontal wind direction shear in the vertical will increase. The vertical dis-

TABLE 5. For the vertical dispersion parameter comparisons, the number of cases within each distance range as a function of release height and of stratification for the full data set.

Release Height	Stratification	Downwind Distance (km) 03 to 06	06 to 15	15 to 55	55 to 1.75	1.75 to 5.40	Total
Elevated	Stable	2	6	18	15	5	46
	Unstable	1	21	69	68	31	190
Near-Surface	Stable	38	44	77	35	4	198
	Unstable	20	37	74	50	14	195

persion parameter comparisons were for relatively short downwind distances, generally less than 1.75 km. At distances greater than 1.75 km downwind during unstable stratification, the vertical dispersion will become limited to the depth of the convectively mixed layer. It is expected that during stable stratification the dispersion in the vertical for the near-surface releases will be limited to the depth of the nocturnal surface layer. For the data listed in Table 1, the measured vertical dispersion parameters were always less than 100 m and most often were less than 50 m. Furthermore, there were no clear indications that the vertical dispersion was approaching a limiting value during transport downwind. We conclude that either the nocturnal mixed depth did not represent an upper limit to the vertical dispersion or that the limiting condition occurred at distances greater than 1.75 km downwind. For the elevated releases during stable stratification, it is not possible to determine from wind speed and temperature profile data whether the release height was above or within the nocturnal mixed-layer depth. The variation with distance downwind of the observed σ_z values for the elevated releases was quite similar except for the Hanford 56-m release conducted during very stable stratification (Hilst and Simpson, 1958). During this trial, there was little change in σ_z for downwind distances beyond 750 m. This may be indicative of vertical dispersion within a stable layer aloft that is essentially decoupled from the surface. Effects such as the contribution to the lateral dispersion due to horizontal wind direction shear in the vertical and the limiting of the vertical dispersion to some finite depth can significantly alter the variation with distance of the vertical and lateral dispersion parameters. The possibility of dramatic changes occurring in the variation of the dispersion parameters with distance is a strong argument against extrapolating the comparison results depicted in Figs. 1 and 2 to larger downwind distances.

It is beyond the scope of this paper to discuss in detail how σ_w and σ_v might vary as a function of height above ground and as a function of atmospheric stability. Cramer (1976) presented power-law approximations which suggest that σ_w would tend to decrease and that σ_v would tend to remain constant with height during stable stratification. The Aerovane data presented in the Hanford-67 data summary (Nickola, 1977) suggest no significant[2] height dependence of σ_v during stable stratification within the layer from 15 to 122 m. Estimation of σ_w and σ_v during stable stratification may prove to be difficult, but then for dispersion from elevated releases in relatively flat terrain, the surface concentrations are usually slight with little of the material reaching the surface. During unstable conditions, the data presented by Izumi and Caughey (1976) would suggest that σ_v is relatively constant within the convectively mixed layer and σ_w tends to increase with height over the lower 25% or so of the mixed layer. Most of this increase in σ_w occurs in the lower 10% of the mixed layer. Cramer's (1976) characterizations of σ_w and σ_v during unstable stratification are in accord with these results, if we limit his characterizations to the lower portions of the mixed layer. This brief discussion does not offer a means for estimating σ_w and σ_v but points out that σ_w is much more dependent on the measurement height than is σ_v. Hence, the usefulness of onsite characterization of dispersion for elevated releases for routine applications will hinge on whether σ_w can be reasonably well characterized using routine equipment, because the surface concentrations are more sensitive to variations in the vertical dispersion parameter than to variations in the lateral dispersion parameter, and because σ_w tends to vary rather rapidly with height.

c. *Comparison of σ_y and σ_z estimates with the Pasquill–Gifford scheme*

In the following discussion, the vertical and lateral dispersion parameters estimated using the characterizations of the dispersion parameters listed in Table 3 are compared with those estimated using the Pasquill–Gifford scheme (Turner, 1970). As can be seen in Tables 1 and 2, the Prairie Grass and Karlsruhe field experiments have measurements of the vertical and lateral velocity variances at release height, measurements of the vertical and lateral dispersion parameters, and the observations necessary to assign Pasquill stability categories as outlined by Turner (1964). Pasquill stability categories could have been assigned to the other field experiments using alternative criteria, such as temperature differences ΔT, or σ_θ. However, use of several different criteria in assigning the categories would have complicated the analysis by providing other possible sources for differences in model performance. It was decided to limit the methodology for assigning the Pasquill categories to that of Turner (1964).

Summaries were made to allow comparison of the performance of the Pasquill–Gifford scheme and of the five models listed in Table 3 in estimating the dispersion parameters. Tables 6 and 7 give the number of cases in each distance range as a function of release height and stratification for the lateral and vertical dispersion parameter comparisons. The comparison results for the lateral dispersion are illustrated in Fig. 3, and the results for the vertical dispersion are illustrated in Fig. 4. The notations used in Figs. 3 and 4 are the same as in Figs. 1 and 2. Comparison of the lateral dispersion results illustrated in Figs. 1 and 3 suggests that the five models (Table 3) per-

[2] Could not reject the null hypothesis that σ_v (approximated by $\sigma_\theta u$) was independent of height, using Friedman two-way layout test (Hollander and Wolfe, 1973).

TABLE 6. For the lateral dispersion parameter comparisons on the partial data set, the number of cases within each distance range as a function of release height and of stratification.

Release Height	Stratification	Downwind Distance (km) 03 to 06	06 to 15	15 to 55	55 to 1 75	1 75 to 5 40	Total
Elevated	Stable			2	2	2	6
	Unstable			15	16	2	33
Near-Surface	Stable	32	32	64	32		160
	Unstable	31	31	62	31		155

TABLE 7. For the vertical dispersion parameter comparisons on the partial data set, the number of cases within each distance range as a function of release height and of stratification.

Release Height	Stratification	Downwind Distance (km) 03 to 06	06 to 15	15 to 55	55 to 1 75	1 75 to 5 40	Total
Elevated	Stable			2	2	2	6
	Unstable		2	30	34	15	81
Near-Surface	Stable	25	25	50	24		124
	Unstable	15	16	32	16		79

formed similarly on the partial and the full data sets. The observable trends in the results were similar, although the overall bias appeared to be different. The Pasquill–Gifford scheme tended to underestimate the lateral dispersion during unstable stratification. For the releases during stable stratification, the Pasquill–

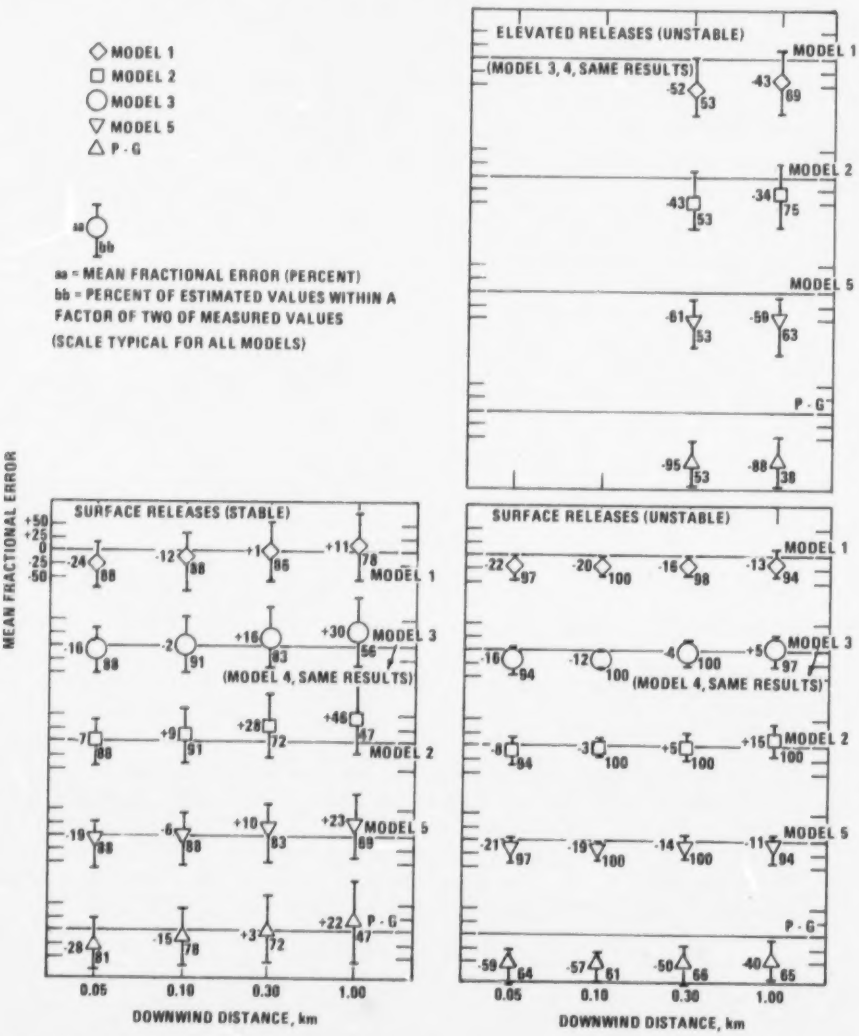

FIG. 3. Comparison of the measured lateral dispersion parameters with those estimated using the five dispersion parameter characterizations listed in Table 3 and using the Pasquill–Gifford (P–G) scheme, for the partial data set.

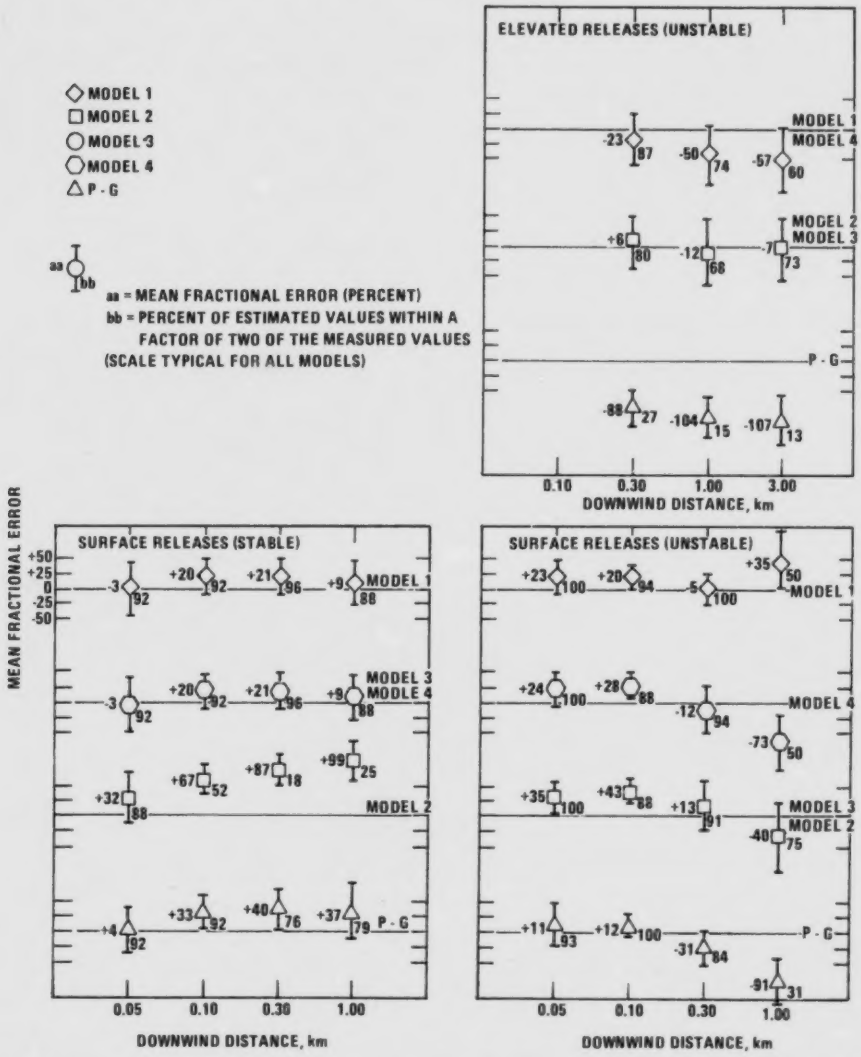

FIG. 4. Comparison of the measured vertical dispersion parameters with those estimated using the first four dispersion parameter characterizations listed in Table 3 and using the Pasquill–Gifford (P–G) scheme, for the partial data set.

Gifford scheme tended to underestimate the lateral dispersion parameter initially, but this bias reversed for the comparisons beyond 0.15 km downwind.

Comparison of the vertical dispersion results illustrated in Figs. 2 and 4 suggests that the first four models listed in Table 3 performed similarly on the partial and full data sets. No results are illustrated for the elevated releases during stable stratification, because there were too few cases for analysis. The trends in the results were similar, although the overall bias appeared different. These shifts of 10–20% in the computed values of the mean fractional error occurred in the analysis from one field experiment to the next, for both the lateral and the vertical dispersion parameter comparisons. Such differences could arise for various reasons (e.g., differences in experimental procedures such as release duration or sampling procedures, differences in processing the velocity variances, and differences in the meteorological instrumentation), but the exact causes from one experiment to the next were not specifically investigated in this analysis. For the elevated releases at Karlsruhe (Thomas *et al.*, 1976; Thomas and Nester, 1976) during unstable stratification, the Pasquill–Gifford scheme had a strong bias to underestimate the vertical dispersion parameter. For the surface releases at Prairie

TABLE 8. For the surface-concentration comparisons, the number of cases within each distance range as a function of release height and of stratification.

Release Height	Stratification	Downwind Distance (km) 03 to 06	06 to 15	15 to 55	55 to 1 75	1 75 to 5 40	Total
Elevated	Stable			2	2	2	6
	Unstable		16	46	46	18	126
Near Surface	Stable	38	44	73	35	4	194
	Unstable	20	36	63	47	13	179

Grass (Barad, 1958; Haugen, 1959) during stable stratification, the Pasquill–Gifford scheme overestimated the vertical dispersion parameter. For the surface releases during unstable stratification, the Pasquill–Gifford scheme initially overestimated the vertical dispersion parameter, but the trend was to underestimate the vertical dispersion parameter at downwind distances beyond 0.15 km.

Studies by Vogt (1977) suggest that the vertical dispersion parameter may be larger for elevated releases during very unstable stratification, because the turbulence resulting from thermal convection reaches a maximum at some distance above the ground. The site aerodynamic surface roughness length for Karlsruhe is about 1 m, which is larger than the roughness length of 0.03–0.30 m typically associated with the data used to develop the Pasquill–Gifford dispersion parameters. Hence, the Pasquill–Gifford scheme underestimated the dispersion parameters for the Karlsruhe data, partly because of the structure of turbulence within a convectively mixed atmosphere and partly because of the site characteristics.

The trends in the Pasquill–Gifford model performance for the near-surface releases are not well understood. The Pasquill–Gifford scheme tended to underestimate the lateral dispersion parameters during unstable stratification, and during stable stratification the trend reversed. The downwind distances were too short for significant contributions by wind direction shear in the vertical. Deposition, if it were to occur, would not help explain the comparison results illustrated for the model estimates of the lateral dispersion parameters. For the vertical dispersion parameter comparisons, the Pasquill–Gifford scheme tended to overestimate during stable stratification and underestimate during unstable stratification. Deposition would explain in part the tendency to underestimate the vertical dispersion parameter for the near-surface releases, but it would not help explain the tendency to overestimate the vertical dispersion parameter during stable stratification. This suggests that, although deposition may occur, it is not a dominant factor.

In summary, the lateral dispersion parameter comparison results suggest that the models employing velocity variances at release height resulted in more estimates within a factor of 2 of the measured lateral dispersion parameters in comparison to the results for the Pasquill–Gifford scheme. Similarly, for the vertical dispersion parameter comparisons, the models employing velocity variances at release height had more estimates within a factor of 2 in comparison to the results for the Pasquill–Gifford scheme. The mean fractional errors were typically smaller with these models, suggesting less overall bias. The standard deviations of the fractional errors were slightly less than those resulting for the Pasquill–Gifford scheme, suggesting that these models had slightly greater precision than the Pasquill–Gifford scheme. Tables C and D in the Appendix present some of the other statistics computed for these comparisons on the partial data set. Since data from only two sites were used in these comparisons, the generality of the results shown for the Pasquill–Gifford model cannot be confirmed.

d. Centerline surface-concentration comparisons

The centerline values of the normalized surface concentration were computed using (3) for each downwind arc and using the first four models listed in Table 3 to estimate the vertical and lateral dispersion parameters. For these estimates, the vertical and lateral velocity variances measured at the release height were used in (1) and (2). Only experiments having measurements of both the vertical and lateral velocity variances and dispersion parameters were selected—Round Hill I, Prairie Grass, and NRTS A and B for the near-surface releases and NRTS and Karlsruhe for the elevated releases. Statistics comparing the estimated concentrations with the measured concentrations initially were computed for each possible combination of release height (elevated and near-surface) and stratification (stable and unstable). The results for five downwind distance ranges were used to assess the variation in the comparison statistics as a function of distance downwind. Table 8 gives the distance ranges used in these analyses and the number of cases in each range as a function of release height and of stratification. There are too few cases for analysis of elevated releases during stable stratification. The distance dependence of the comparison statistics is illustrated in Fig. 5. To jointly illustrate the distance dependence of the mean and standard deviation of the fractional errors, (3) was used to compute the ratio r of the estimated concentration divided by measured concentration implied by the computed mean fractional error $\bar{e}$, as $r = (2 + \bar{e})/(2 - \bar{e})$. Similarly, the error bars depicted in Fig. 5 ($\bar{e}$ plus or minus one standard deviation) were expressed in terms of such a ratio. In addition, the actual values for the mean and the standard deviation of the fractional errors are indicated in Fig. 5. Because the number of cases available for analysis at each distance varied, it is important to assess the results given in Fig. 5

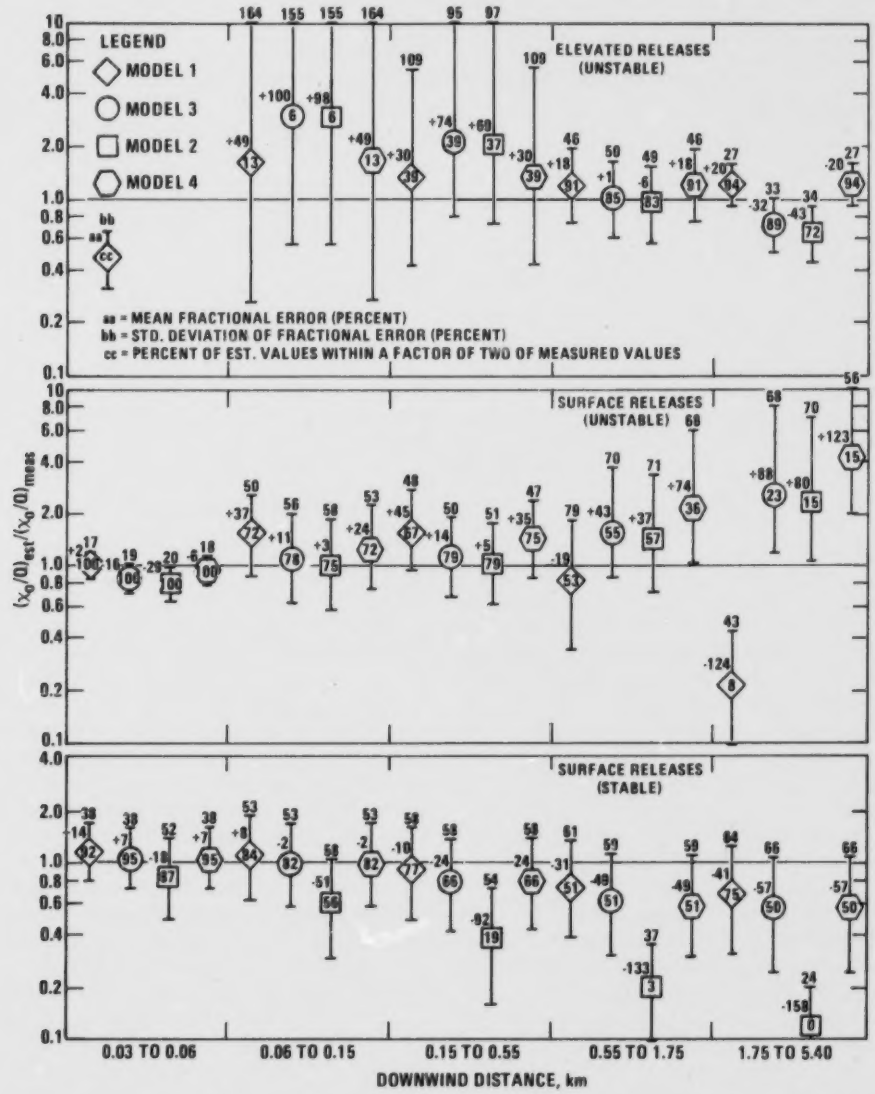

FIG. 5. Comparison of the measured surface concentration values (χ_o/Q) with those estimated using the Gaussian plume model, using the first four dispersion parameter estimation schemes listed in Table 3. The bars depict the mean fractional error plus or minus one standard deviation. The number within the symbol is the percentage of the cases with estimates within a factor of two of the measured concentrations.

with reference to Table 8. For models using nearly the same characterization of the vertical and lateral dispersion parameters, the observable trends in the comparison statistics illustrated in Fig. 5 are similar. For instance, Models 1 and 3 involve nearly the same treatment for near-surface releases during stable stratification; the results for these two models during stable stratification (see Fig. 5, bottom) were nearly the same. For near-surface and elevated releases during unstable stratification, Models 2 and 3 result in similar characterizations of the dispersion parameters; the performance of these two models was quite similar for releases during unstable stratification (Fig. 1). For near-surface releases, the precision, as characterized by the standard deviation of the fractional errors, tended to decrease as downwind distance increased. An increase in the standard deviation of the fractional errors was considered a decrease in precision. In the modeling results, the trend toward decreased precision with increasing downwind distance for surface

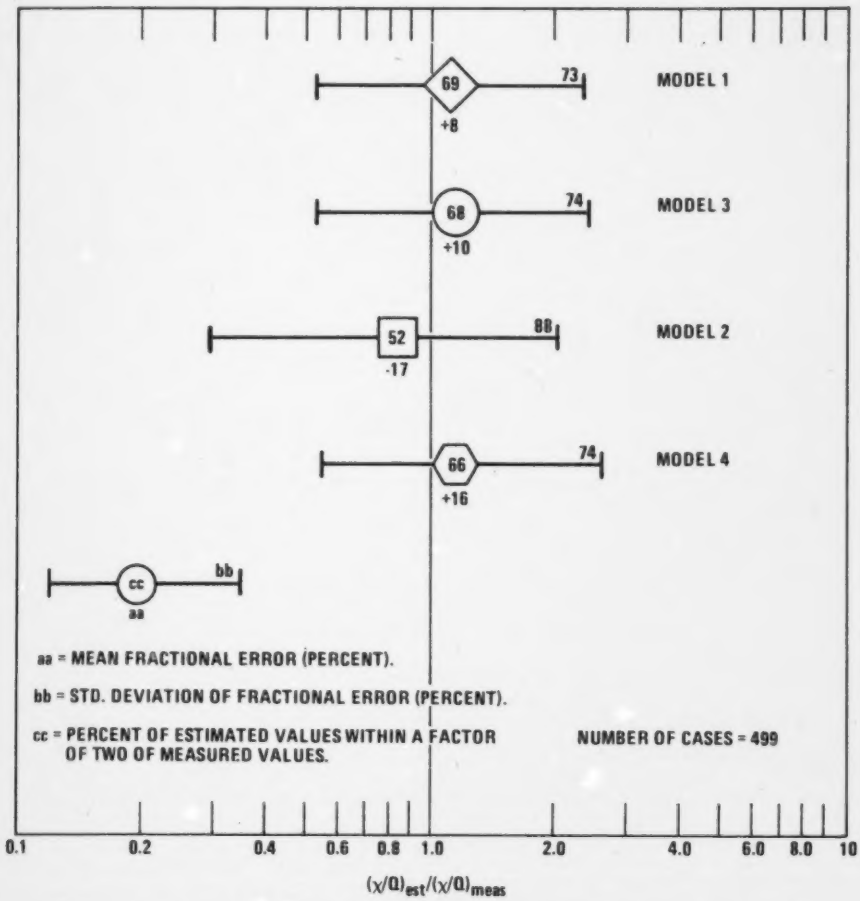

FIG. 6. The ratio between the estimated and measured surface concentration values (χ_0/Q), for all stability conditions and downwind distances.

releases contrasted sharply with the increased precision with increasing downwind distance for elevated releases. The latter result is to be expected when one considers that for elevated releases, measurement errors, if present, will be most noticeable for the concentration values where the plume is just beginning to reach the surface. Also, some of the scatter at the nearest downwind arc for the elevated releases may reflect occasional transport of the plume to the surface within a convectively mixed layer. Such transport would result in a few sporadic high concentration measurements.

The large underestimates at distances beyond 1 km by Draxler's scheme (Model 1) for surface releases during unstable stratification were expected. Extrapolation of Draxler's characterization of the vertical dispersion parameters for near-surface releases during unstable stratification to distances downwind greater than 1 km gave large overestimates of the vertical dispersion parameter. The underestimation by Cramer's model (Model 2) of the vertical dispersion for surface releases during unstable stratification at distances beyond 1 km was reflected in the tendency for Models 2 and 3 to overestimate the magnitude of the concentrations at these distances (Fig. 5, middle).

Fig. 6 summarizes the results illustrated in Fig. 5, combining the results for all distances and releases. The six cases during stable stratification for the elevated releases are not included in the results illustrated in Fig. 6 but are summarized in Table E of the Appendix, along with the other statistics computed as part of the analysis.

e. Maximum concentrations from elevated releases

For this analysis of the peak concentrations, the NRTS data reported by Islitzer (1961) and Bowne (1960) were used. The NRTS experiment was well conceived, having samplers spaced about 100 m apart on the 3200-m downwind arc and about 14 m apart on the 100-m downwind arc. This network of 100

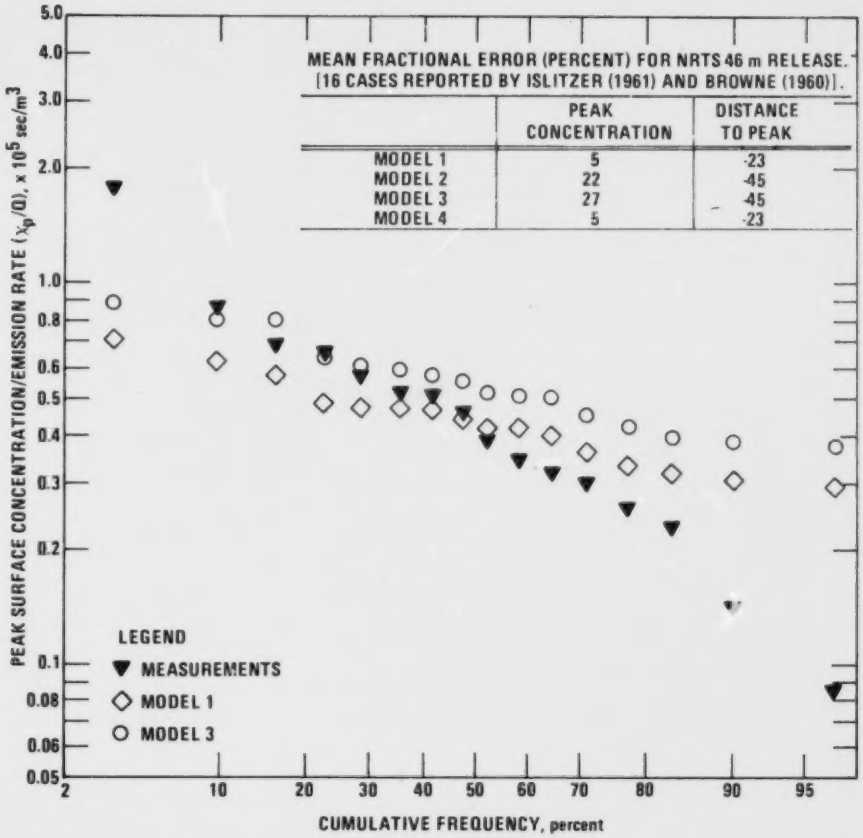

FIG. 7. Cumulative frequency plot of the estimates and measurements of the peak surface concentration divided by the emission rate for the NRTS A and B 46-m releases. All 16 measurements were made during unstable stratification. The table insert gives the mean fractional error (percent) computed over all 16 cases for the estimates of the peak and of the distance to the peak concentration.

samplers—four times the number employed in the Karlsruhe experiments (Thomas *et al.*, 1976)—allowed the location and magnitude of the peak surface concentration for each trial to be specified (Bowne, 1960; Islitzer, 1961). The location and magnitude of the peak surface concentration were estimated using the first four characterizations of dispersion listed in Table 3. These estimates were made using the reported values for σ_a and σ_e and, assuming, as did Islitzer (1961), no reflection by the earth's surface.

Fig. 7 depicts some of the comparisons of the model estimates with the measured values of the peak concentration. Because Models 1 and 4 use the same characterization of dispersion for elevated releases during unstable stratification, results are shown only for Model 1. And because the results for Model 2 were nearly identical to (typically 5% less than) the results for Model 3, only the latter are shown. The table appearing in Fig. 7 lists the mean fractional error for each of the models of the magnitude and location of the peak concentration. All four models tended to underestimate the highest values of peak concentration. The number of estimates within a factor of 2 of the 16 measured peak concentrations was 13, 12, 11, and 13, for Models 1–4, respectively. The tendency to underestimate the distance to the peak concentration is related to the tendency for the models to overestimate the vertical dispersion parameter. These releases were close enough to the surface that one cannot reliably infer how these models would characterize the dispersion and resulting surface concentrations for sources tall enough to be well within the convectively mixed layer.

f. Comparison of χ_0 estimates with the Pasquill–Gifford scheme

In the following discussion, comparison is made of centerline values of the surface concentration estimated using the first four characterizations of the dispersion parameters listed in Table 3 versus those estimated using the Pasquill–Gifford scheme.

TABLE 9. For the surface-concentration comparisons with the Pasquill-Gifford scheme, the number of cases within each distance range as a function of release height and of stratification.

Release Height	Stratification	Downwind Distance (km)					
		0.3 to 0.6	0.6 to 1.5	1.5 to 5.5	5.5 to 1.75	1.75 to 5.40	Total
Elevated	Stable			2	2	2	6
	Unstable			14	14	2	30
Near Surface	Stable	25	25	50	24		124
	Unstable	15	16	32	16		79

The performance of the five models in estimating the centerline values of the surface concentration were summarized using the distance ranges listed in Table 8. Table 9 gives the number of cases in each range as a function of release height and of stratification. Fig. 8 illustrates the distance dependence of the comparison results. The notations used in Fig. 8 are the same as those described for Fig. 5. Comparison of Figs. 5 and 8 suggests that the models performed similarly on the partial and the full data sets. Fig. 9 summarizes the results for each model for all downwind distances. No comparisons are included for elevated releases during stable stratification, because there were so few cases. Table F in the Appendix presents some of the other statistics computed for the comparisons using the partial data set. The similarities of the overall performance of the models on the full and partial data sets can be seen by comparing Figs. 6 and 9. The major difference is that the models tended to overestimate concentrations more often with the Prairie Grass and Karlsruhe data than with the full data set.

The Pasquill–Gifford model tended to overestimate the surface concentrations for the near-surface releases and to underestimate the surface concentrations for the elevated releases during unstable stratification. For the near-surface releases during stable stratification, the performance of the Pasquill–Gifford model was similar to that of the other models.

Except for the results explained earlier for Model 2 during stable stratification, the characterizations of the dispersion parameters employing velocity variances at the effective release height resulted in more estimates within a factor of 2 of the measured concentration values than did the Pasquill–Gifford scheme. The mean fractional errors and their standard deviation were typically smaller by these models than by the Pasquill–Gifford scheme, suggesting less overall bias and greater precision with these models.

3. Conclusions

The performance of dispersion parameter estimation schemes suggested by Cramer (1976), Draxler (1976), and Pasquill (1976), allowing the use of onsite measurements of atmospheric turbulence, were compared using data from field experiments. Comparison of the lateral dispersion parameter schemes suggested by Pasquill and by Cramer, suggest that, of the two, Cramer's scheme performs better for the elevated releases and Pasquill's scheme performs better for the near-surface releases. This result is consistent with the intended use of Cramer's scheme for tall stack dispersion estimates. Variations in the performance of the lateral dispersion parameter estimates by Pasquill's (1976) scheme were reported by Doran *et al.* (1978a), based on analyses using the Hanford-67 data (Nickola, 1977). They found that by choosing a near-surface height for the measurements of the lateral velocity fluctuations, the performance of Pasquill's scheme could be improved. Aside from the Hanford-67 data, near-surface measurements of the lateral velocity variances were not routinely available for the field experiments having elevated releases. The solution suggested in this discussion is to choose the form for f_y that provides the best estimates of the lateral dispersion parameters while employing velocity variances measured at plume level. Draxler's characterization of the lateral dispersion parameters performed almost as well as Pasquill's for the near-surface releases and almost as well as Cramer's for the elevated releases. Comparison of Cramer's and Draxler's schemes for characterizing the vertical dispersion parameter suggest that both perform well for unstable conditions. For stable stratification, Draxler's scheme performed better in characterizing the observed vertical dispersion parameters. Use of the nocturnal mixed-layer depth was determined to be an important consideration in the use of Cramer's model for characterizing the dispersion parameters during stable stratification.

Choosing forms for f_y and f_z that are invariant with height resulted in little overall loss in model performance. The vertical dispersion parameter estimates by Model 3 were within a factor of 2 of the measured values in 79% of the 629 cases used in this analysis, with a mean fractional error of −4%. This compared favorably with the results for Draxler's model of 80% of the vertical dispersion parameter estimates within a factor of two of the measured values and a mean fractional error of −5%. The lateral dispersion parameter estimates by Model 3 were within a factor of two of the measured values in 85% of the 2026 cases used in this analysis with a mean fractional error of 4%. The results for Draxler's model on the same data for the lateral dispersion parameter estimates were 88% within a factor of 2 of the measured values and a mean fractional error of −0.3%. There are important limitations to these results, especially with respect to the lateral dispersion parameter comparisons. As discussed by Doran *et al.* (1978b), the form of f_y is a function of several factors, such as sampling duration, averaging time, release

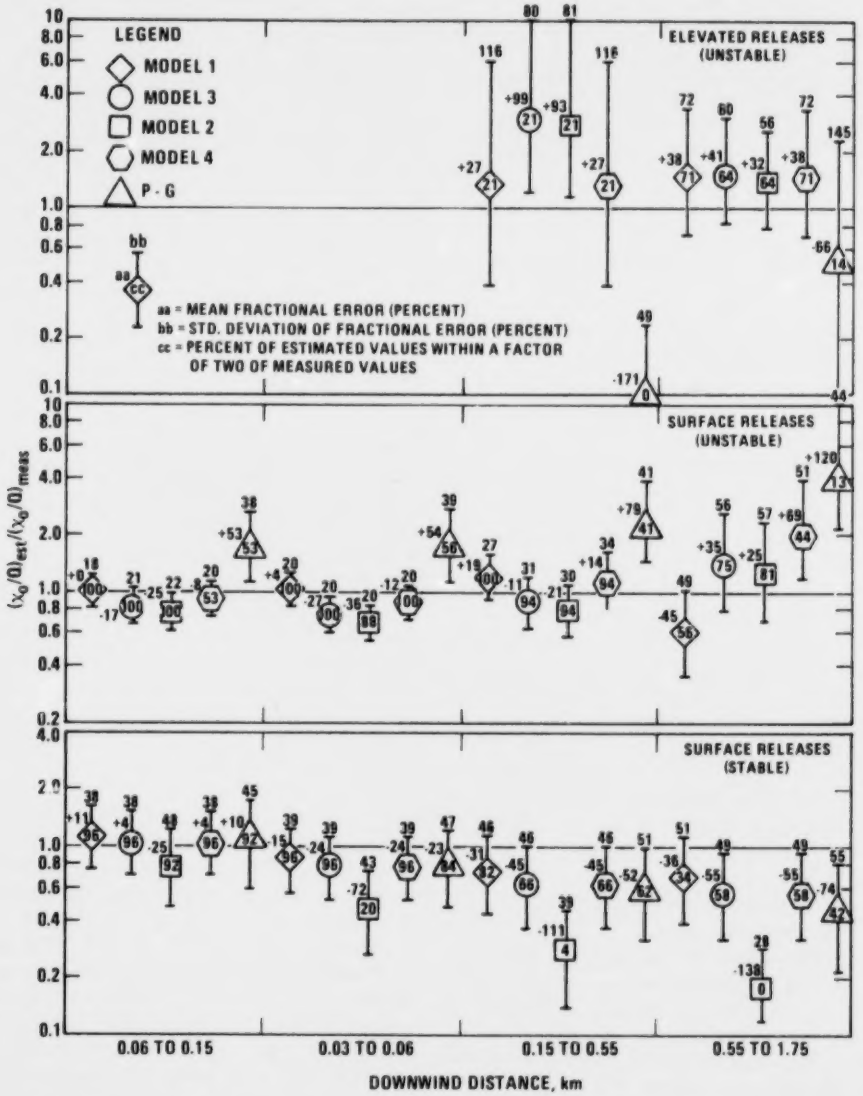

FIG. 8. Comparison of the measured surface concentrations values (χ_0/Q) with those estimated using the Gaussian plume model, using the first four dispersion parameter estimation schemes listed in Table 3 and the Pasquill–Gifford dispersion scheme. The bars depict the mean fractional error plus or minus one standard deviation. The number within the symbol is the percentage of the cases with estimates within a factor of two of the measured concentrations.

height, and stability. Most of the comparisons presented are for sampling durations of approximately 30 min with an averaging time of 5 s for σ_a. The conclusions presented are most applicable to modeling analyses having similar source–receptor relationships and having similar meteorological data as were encountered in this analysis.

The limited comparisons using the Prairie Grass and Karlsruhe data suggested that models employing the velocity variances at the release height resulted in less average bias in characterizing the dispersion parameters in comparison to the results obtained using the Pasquill–Gifford scheme to characterize the dispersion parameters. These conclusions were based on computations in which turbulence measurements were available at the final plume height.

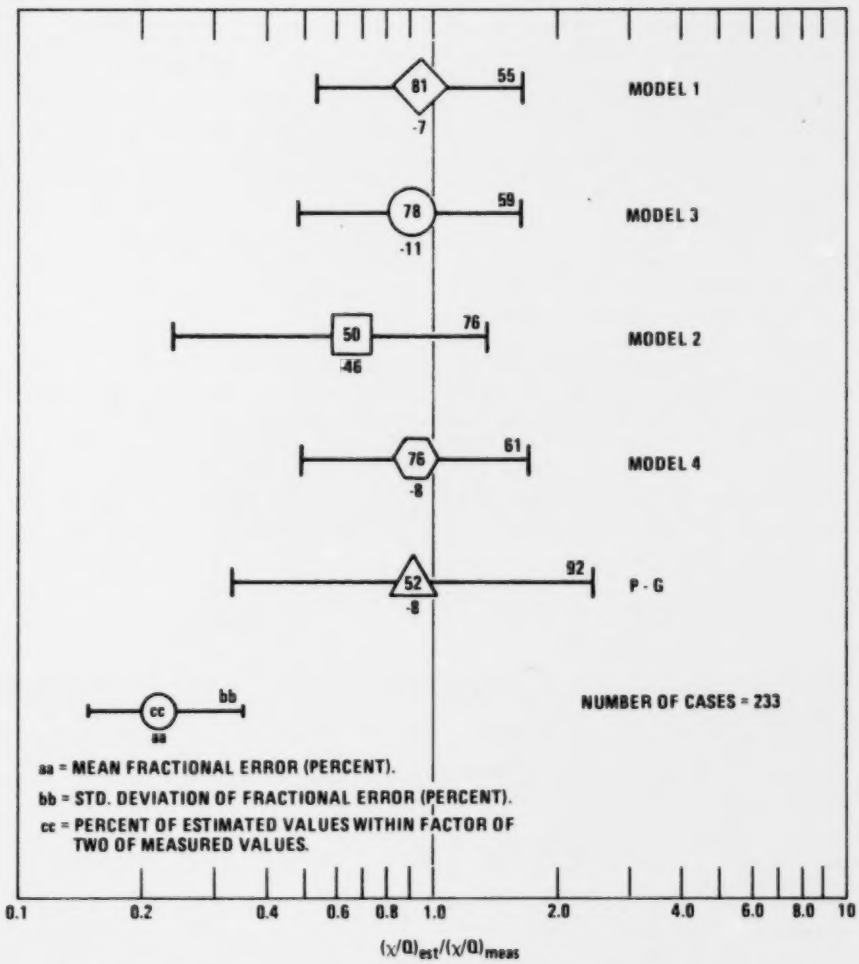

FIG. 9. The ratio between the estimated and measured surface concentration values (χ_0/Q), for all stability conditions and downwind distances, using the partial data set.

The performance of dispersion parameter schemes suggested by Cramer and Draxler in estimating centerline values of the surface concentration was compared using data from field experiments. Draxler's characterization of the dispersion performed best overall in estimating the concentration values. Cramer's scheme performed well for the releases during unstable stratification.

Choosing forms for f_y and f_z that are invariant with height resulted in little loss in model performance for estimating the surface concentration values. In view of this result, it seems justifiable to choose forms for f_y and f_z that are invariant with height until it is demonstrated that including release-height effects significantly improves performance. In that event, the forms for f_y and f_z might, in some way, explicitly include the release height, providing a continuous description of the release-height dependence. The limited surface concentration comparisons using the Prairie Grass and Karlsruhe data suggest that Models 1, 2, 3 and 4 for characterizing the dispersion parameters result in less average bias, and greater precision in characterizing the centerline values of the surface concentration, than does the Pasquill–Gifford scheme. It is expected that use of onsite turbulence measurements at the effective release height would tailor, to a first order, the dispersion parameter estimates to the existing release-height and site-roughness effects. Such tailoring would be expected to increase the precision and reduce the bias of the estimates; however, this needs to be confirmed through further testing using other data. These conclusions are based on

computations in which turbulence measurements were available at the final effective height of release. If such turbulence measurements were not available, the errors induced by estimating the turbulence intensities at plume level might have resulted in a loss of performance, possibly rendering these estimates of the concentration values no better than estimates by the Pasquill–Gifford scheme.

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APPENDIX

Tables of Results

Tables A and B summarize, for the comparisons using the full data set, the results for several statistical descriptors that can be used in evaluating model estimates of the lateral and vertical dispersion parameters. Tables C and D summarize the results for the statistical descriptors for the comparisons with the Pasquill–Gifford scheme using the partial data set containing only data from Prairie Grass and Karlsruhe.

Tables E and F summarize the results for several statistical descriptors that can be used in evaluating model estimates of surface concentration values. The results presented in Table E allow comparison of Models 1, 2, 3 and 4 on the full data set. Table F allows comparison of these four models and the Pasquill–Gifford scheme on the data from Prairie Grass and Karlsruhe only.

TABLE A. Summary, for the full data set, comparing the lateral dispersion parameters measured with those estimated using the five dispersion parameter characterizations listed in Table 3. The field studies that comprise the full data set are listed in Tables 1 and 2.

	Stable Stratification					Unstable Stratification				
Dispersion Characterization	Model 1	Model 2	Model 3	Model 4	Model 5	Model 1	Model 2	Model 3	Model 4	Model 5
Elevated Releases										
Number of cases	292	292	292	292	292	283	283	283	283	283
Number of estimates within a factor of two	236	247	236	236	215	271	271	271	271	265
Fractional error, percent										
Mean	-25	-10	-25	-25	-40	-11	-2	-11	-11	-27
Median	-22	-7	-22	-22	-38	-9	3	-9	-9	-24
Standard deviation	47	47	47	47	46	30	30	30	30	30
Residual (est. -meas.), m										
Mean	-45	-13	-45	-45	-69	-21	-5	-21	-21	-42
Median	-13	-3	-13	-13	-28	-5	1	-5	-5	-15
Standard deviation	132	139	132	132	139	87	92	87	87	88
Correlation of est. to meas.										
Pearson's r	0.749	0.762	0.749	0.749	0.739	0.797	0.796	0.797	0.797	0.811
Kendall's tau	0.739	0.750	0.739	0.739	0.730	0.846	0.847	0.846	0.846	0.842
Spearman's r_s	0.893	0.900	0.893	0.893	0.886	0.958	0.962	0.958	0.958	0.960
Surface Releases										
Number of cases	623	623	623	623	623	828	828	828	828	828
Number of estimates within a factor of two	534	493	519	519	521	748	591	702	702	727
Fractional error, percent										
Mean	-3	25	2	2	-4	14	40	20	20	9
Median	-3	24	1	1	-4	6	38	15	15	6
Standard deviation	49	47	49	49	48	45	44	42	42	41
Residual (est. -meas.), m										
Mean	36	57	-22	-22	-36	-7	154	58	58	33
Median	-0.4	8	0.1	8	-0.6	-2	63	19	19	5
Standard deviation	299	229	162	162	180	138	258	167	167	137
Correlation of est. to meas.										
Pearson's r	0.799	0.824	0.825	0.825	0.786	0.717	0.788	0.735	0.735	0.784
Kendall's tau	0.799	0.800	0.790	0.790	0.749	0.749	0.769	0.758	0.758	0.759
Spearman's r_s	0.941	0.943	0.936	0.936	0.940	0.900	0.914	0.907	0.907	0.906

TABLE B. Summary, for the full data set, comparing the vertical dispersion parameters measured with those estimated using the first four dispersion parameter characterizations listed in Table 3. The field studies that comprise the full data set are listed in Tables 1 and 2.

	Stable Stratification				Unstable Stratification			
Dispersion Characterization	Model 1	Model 2	Model 3	Model 4	Model 1	Model 2	Model 3	Model 4
Elevated Releases								
Number of cases	46	46	46	46	190	190	190	190
Number of estimates within a factor of two	36	26	36	36	167	155	155	167
Fractional error, percent								
Mean	-7	55	-17	-17	-17	16	16	-17
Median	-1	56	-16	-16	-6	25	25	-6
Standard deviation	59	61	57	57	47	48	48	47
Residual (est. -meas.), m								
Mean	-6	14	-6	-6	-50	-5	-5	-50
Median	-0.1	6	-1	-1	-3	9	9	-3
Standard deviation	24	25	23	23	180	168	168	180
Correlation of est. to meas.								
Pearson's r	0.393	0.590	0.493	0.493	0.515	0.567	0.567	0.515
Kendall's tau	0.573	0.617	0.590	0.590	0.743	0.749	0.749	0.743
Spearman's r_s	0.748	0.767	0.753	0.753	0.902	0.906	0.906	0.902
Surface Releases								
Number of cases	198	198	198	198	195	195	195	195
Number of estimates within a factor of two	174	98	174	174	128	131	131	116
Fractional error, percent								
Mean	1	64	1	1	0	-25	-25	-47
Median	8	66	8	8	0	-12	-12	-43
Standard deviation	46	49	46	46	72	66	66	67
Residual (est. -meas.), m								
Mean	-0.02	-11	-0.02	-0.02	240	-49	-49	-59
Median	0.4	0.4	0.04	0.04	-0.1	-2	-2	-5
Standard deviation	4	18	4	4	1249	145	145	155
Correlation of est. to meas.								
Pearson's r	0.822	0.791	0.822	0.822	0.702	0.741	0.741	0.702
Kendall's tau	0.678	0.668	0.678	0.678	0.729	0.721	0.721	0.710
Spearman's r_s	0.850	0.844	0.850	0.850	0.892	0.891	0.891	0.884

TABLE C. Summary, for the partial data set, comparing the lateral dispersion parameters measured with those estimated using the five dispersion parameter characterizations listed in Table 3. The partial data set consists of the Project Prairie Grass and the Karlsruhe data.

	Stable Stratification						Unstable Stratification					
Dispersion Characterization	Model 1	Model 2	Model 3	Model 4	Model 5	P-G	Model 1	Model 2	Model 3	Model 4	Model 5	P-G
Elevated Releases												
Number of cases	6	6	6	6	6	6	33	33	33	33	33	33
Number of estimates within a factor of two	0	0	0	0	0	0	21	22	21	21	19	11
Fractional error, percent												
Mean	-161	-156	-161	-161	-167	-148	-47	-38	-47	-47	-60	-91
Median	-166	-163	-166	-166	-170	-157	-35	-29	-35	-35	-52	-86
Standard deviation	11	13	11	11	8	15	56	54	56	56	50	44
Residual (est. -meas.), m												
Mean	-528	-516	-528	-528	-541	-501	-129	-115	-129	-129	-145	-173
Median	-516	-510	-516	-510	-526	-498	-52	-36	-52	-52	-74	-102
Standard deviation	420	410	420	420	429	401	204	193	204	204	202	210
Correlation of est. to meas.												
Pearson's r	0.850	0.850	0.850	0.850	0.850	0.850	0.571	0.654	0.571	0.571	0.680	0.674
Kendall's tau	0.894	0.894	0.894	0.894	0.894	0.894	0.483	0.562	0.483	0.483	0.562	0.608
Spearman's r_s	0.956	0.956	0.956	0.956	0.956	0.956	0.673	0.741	0.673	0.673	0.741	0.791
Surface Releases												
Number of cases	160	160	160	160	160	160	155	155	155	155	155	155
Number of estimates within a factor of two	136	118	128	128	131	112	151	153	152	152	152	97
Fractional error, percent												
Mean	-4	21	9	9	4	-3	-18	3	-6	-6	-16	-51
Median	8	31	18	18	14	8	-16	2	-6	-6	-15	-48
Standard deviation	56	58	58	58	55	64	24	25	25	25	24	35
Residual (est. -meas.), m												
Mean	-9	-1	-5	-5	6	-8	-8	4	-1	-1	-6	-19
Median	0.5	3	2	2	1	0.6	-3	1	-1	-1	-3	-9
Standard deviation	69	67	68	68	67	71	19	22	20	20	19	27
Correlation of est. to meas												
Pearson's r	0.315	0.383	0.336	0.336	0.384	0.162	0.896	0.895	0.896	0.896	0.894	0.790
Kendall's tau	0.648	0.657	0.652	0.652	0.656	0.551	0.854	0.854	0.853	0.853	0.853	0.773
Spearman's r_s	0.805	0.822	0.814	0.814	0.819	0.716	0.972	0.972	0.972	0.972	0.972	0.919

TABLE D. Summary, for the partial data set, comparing the vertical dispersion parameters measured with those estimated using the first four dispersion parameter characterizations listed in Table 3. The partial data set consists of the Project Prairie Grass and the Karlsruhe data.

	Stable Stratification					Unstable Stratification				
Dispersion Characterization	Model 1	Model 2	Model 3	Model 4	P-G	Model 1	Model 2	Model 3	Model 4	P-G
Elevated Releases										
Number of cases	6	6	6	6	6	81	81	81	81	81
Number of estimates within a factor of two	0	5	0	0	2	60	58	58	60	15
Fractional error, percent										
Mean	-127	-40	-127	-127	-78	-43	-7	-7	-43	-100
Median	-133	-59	-139	-139	-94	-31	5	5	-31	-100
Standard deviation	16	42	16	16	22	55	58	58	55	37
Residual (est. -meas.), m										
Mean	-55	-15	-54	-54	-40	-114	-62	-62	-114	-150
Median	-60	-24	-59	-24	-33	-26	4	4	-26	-63
Standard deviation	38	22	35	35	29	262	237	237	262	253
Correlation of est. to meas.										
Pearson's r	0.866	0.868	0.872	0.872	0.871	0.527	0.625	0.625	0.527	0.786
Kendall's tau	0.894	0.894	0.894	0.894	0.894	0.571	0.586	0.586	0.571	0.644
Spearman's r_s	0.956	0.956	0.956	0.956	0.956	0.749	0.759	0.759	0.749	0.804
Surface Releases										
Number of cases	124	124	124	124	124	79	79	79	79	79
Number of estimates within a factor of two	114	50	114	114	102	70	70	70	67	62
Fractional error, percent										
Mean	14	74	14	14	31	18	13	13	-9	-26
Median	13	74	13	13	24	15	22	22	1	-12
Standard deviation	38	42	38	38	41	39	49	49	53	50
Residual (est. -meas.), m										
Mean	0.5	11	0.5	0.5	2	12	-19	-19	-26	-28
Median	1	7	1	1	2	1	2	2	0.1	-1
Standard deviation	4	12	4	4	5	59	102	102	107	103
Correlation of est. to meas.										
Pearson's r	0.873	0.849	0.873	0.873	0.829	0.866	0.613	0.613	0.572	0.793
Kendall's tau	0.759	0.713	0.759	0.759	0.712	0.855	0.842	0.842	0.836	0.878
Spearman's r_s	0.905	0.880	0.905	0.905	0.861	0.968	0.963	0.963	0.960	0.971

TABLE E. Summary, comparing the measured surface concentration values with those estimated using the Gaussian plume model (x_0/Q), using the first four dispersion parameter characterizations listed in Table 3.

	Stable Stratification				Unstable Stratification			
Dispersion Characterization	Model 1	Model 2	Model 3	Model 4	Model 1	Model 2	Model 3	Model 4
Elevated Releases								
Number of cases	6	6	6	6	126	126	126	126
Number of estimates within a factor of two	0	1	0	0	74	70	79	79
Fractional error, percent								
Mean	-200	8	-193	-193	27	29	36	27
Median	-200	19	-198	-198	16	7	17	16
Standard deviation	< 1	168	7	7	92	99	97	92
Residual (est. -meas.), sec/m³ x 10^6								
Mean	-302	731	-299	-299	403	720	993	403
Median	-224	238	-228	-228	128	16	58	128
Standard deviation	250	947	250	250	2386	2704	2881	2386
Correlation of est. to meas.								
Pearson's r	0.044	0.297	0.044	0.044	0.705	0.680	0.674	0.705
Kendall's tau	0.298	0.298	0.298	0.298	0.635	0.542	0.541	0.635
Spearman's r_s	0.359	0.359	0.359	0.359	0.797	0.701	0.699	0.797
Surface Releases								
Number of cases	194	194	194	194	179	179	179	179
Number of estimates within a factor of two	149	64	140	140	114	126	126	112
Fractional error, percent								
Mean	-6	-77	-18	-18	9	15	23	45
Median	-14	-91	-27	-27	15	-0	11	26
Standard deviation	56	65	57	57	72	62	61	62
Residual (est. -meas.), sec/m³ x 10^6								
Mean	626	-490	295	295	56	-50	-25	16
Median	-35	-431	-85	-85	9.3	-0.3	0.5	5.4
Standard deviation	3082	3221	2652	2652	213	239	220	209
Correlation of est. to meas.								
Pearson's r	0.797	0.655	0.806	0.806	0.942	0.939	0.941	0.942
Kendell's tau	0.789	0.773	0.791	0.791	0.840	0.844	0.843	0.842
Spearman's r_s	0.939	0.931	0.940	0.940	0.959	0.960	0.960	0.960

TABLE F. Summary, comparing the measured surface concentration values with those estimated using the Gaussian plume model (χ_0/Q), using the first four dispersion parameter characterizations listed in Table 3, and the Pasquil-Gifford dispersion parameter characterization. The data set consists of the Project Prairie Grass and the Karlsruhe data.

	Stable Stratification					Unstable Stratification				
Dispersion Characterization	Model 1	Model 2	Model 3	Model 4	P-G	Model 1	Model 2	Model 3	Model 4	P-G
Elevated Releases										
Number of cases	6	6	6	6	6	30	30	30	30	30
Number of estimates within a factor of two	0	1	0	0	0	15	14	14	15	4
Fractional error, percent										
Mean	-200	8	-196	-196	-95	33	59	66	33	-109
Median	-200	19	-198	-198	-179	36	49	53	36	-195
Standard deviation	<1	168	7	7	142	92	74	74	92	121
Residual (est -meas.), sec/m^3 x 10^6										
Mean	-302	731	-299	-299	-35	894	1276	1631	894	-362
Median	-224	238	-228	-228	-156	179	499	538	179	-724
Standard deviation	250	947	250	250	452	2059	1953	2361	2059	1819
Correlation of est. to meas.										
Pearson's r	0.044	0.297	0.044	0.044	0.063	0.178	0.168	0.146	0.178	-0.166
Kendall's tau	0.298	0.298	0.298	0.298	0.298	0.328	0.234	0.215	0.328	0.187
Spearman's r_s	0.359	0.359	0.359	0.359	0.359	0.439	0.360	0.337	0.439	0.063
Surfaces Releases										
Number of cases	124	124	124	124	124	79	79	79	79	79
Number of estimates within a factor of two	102	30	95	95	85	72	72	76	68	32
Fractional error, percent										
Mean	-20	-91	-33	-33	-38	-1	-15	-6	16	77
Median	-26	-99	-37	-37	-36	7	-24	-15	6	82
Standard deviation	47	56	48	48	57	38	40	40	44	47
Residual (est -meas.), sec/m^3 x 10^6										
Mean	459	-746	109	109	-83	7	-143	-105	-48	419
Median	-143	-790	-223	-223	-174	4	-26	-15	4	93
Standard deviation	3446	3837	2955	2955	4060	187	283	247	211	685
Correlation of est. to meas.										
Pearson's r	0.802	0.630	0.813	0.813	0.607	0.974	0.964	0.966	0.970	0.911
Kendell's tau	0.832	0.815	0.832	0.832	0.781	0.910	0.920	0.914	0.912	0.851
Spearman's r_s	0.958	0.953	0.959	0.959	0.925	0.988	0.990	0.989	0.988	0.971

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